Balloon Remote Sensing of Atmospheric gases by FTIR solar absorption spectrometry

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Abstract.
The JPL MkI V interferometer is a balloon-borne FTIR spectrometer. Its broad bandpass and high spectral resolution allow many different atmospheric gases to be measured simultaneously.

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Summary.

Remote sensing of the Earth's atmosphere by viewing the limb provides a high sensitivity to trace gases because of the very long path lengths that are attainable. This makes the results insensitive to local contamination or wall effects which can cause significant systematic errors in in-situ sampling methods. The spatial resolution is, however, much poorer: Typically, the bulk of the absorbing gas along a limb path will be spread over a volume measuring 350 km horizontally and 2 km vertically.

The solar absorption technique has been employed for many years as a tool for atmospheric remote sensing and holds a number of advantages over remote sensing techniques which employ thermal emission. Its main attraction is that the sun, being very bright and stable, allows high signal-to-noise ratio spectra to be recorded rapidly. This is especially true at short wavelengths 2-5 μm, where the atmospheric Planck function is very weak and very temperature-dependent. Moreover, for solar absorption spectrometry, the instrument optics need not be cooled since their thermal emission is negligible compared with the solar radiance, even at 12 μm. Solar absorption spectra arc also self-calibrating in the sense that tbc zero level and the continuum level can be determined from the spectrum itself, the former from opaque regions (e.g. saturated lines and outside the spectral bandpass) where the signal is known to be zero, and the latter from highly transparent regions between the absorption lines. ‘1’bus, observation time need not be wasted viewing, cold and warm calibration targets, as is necessary in thermal emission spectrometry. Of course, the solar absorption technique also has disadvantages: One can obtain profiles only at sunset or sunrise or by daytime altitude changes; solar absorption features can confuse the spectral fitting; and the sunset/sunrise. variations of gases can cause ambiguity in the retrieved profiles.

The JPL MkIV Interferometer is a high resolution FTIR spectrometer built at JPL in 1984 for atmospheric remote sounding. It shares many similarities with the ATMOS instrument (Farmer et al., 1987) which flew 4 times on the Shuttle. The most noteworthy improvement is (hat the MkIV employs an lnSb photodiode in parallel with its HgCdTe photoconductor in order to receive tbc short wavelengths, which are reflected from a dichroic. Thus, the entire 650-5700 cm^{-1} spectral region is measured simultaneously, rather than being divided into narrower regions which are observed sequentially. This arrangement confers a surprising number of advantages: (i) Two moving parts (the filter wheel & tbc field stop wheel) are eliminated, (ii) the InSb photodiode is a much more linear detector than a HgCdTe photoconductor and so its zero offsets arc much smaller, (iii) a greater number and wider choice of spectral lines are available for analysis, (iv) all gases are measured at the same time in the same airmass, greatly simplifying the interpretation of the retrieved profiles.

A disadvantage employing a very wide spectral domain is that the signal-to-noise ratio easily becomes limited by the dynamic range of the digitizer, which for MkIV is effectively 19 bits. While for strongly absorbing gases this is not a concern, for gases whose absorption features are comparable with the noise level digitization can be a major source of uncertainty.

Calculations have revealed that for our InSb photodiode digitization is our leading noise term, closely followed by source photon noise. 1 'or our } IgCdTe photoconductor, detector noise is the leading noise term closely followed by digitizer noise.

A two axis suntracker, designed and built by the University of Denver, supplied the interferometer with a direct beam of solar radiation along its optical axis, irrespective of the orientation of the gondola. The suntracker imaged a portion of the direct solar beam onto a silicon quadrant detector in order to provide error signals for the azimuthal and elevation servo systems. A 950 nm long pass filter minimized the susceptibility of the suntracker to scattered radiation. This system provided pointing accuracy of ±0.02° under bright sun conditions. Under dimmer conditions electrical offsets could cause much larger pointing errors unless they were carefully nulled prior to flight.

The field of view of the interferometer was defined by a 0.75m focal length off-axis paraboloid which imaged the interferometrically modulated solar disk onto cold circular field stops inside the detector dewars. This admitted a 4.3 mrad diameter portion of the solar disk to the 1 IgCdTe detector and a 3.6 mrad diameter portion 10 the lnsb detector. The advantage of not rejecting unused portions of the solar disk before they enter the interferometer is that the telescope and collimating optics are eliminated. The only disadvantage is that wedge angle on the optical components has to be large enough to displace the multiply reflected solar beam by a full solar diameter, rather than just the instrumental FOV diameter. Omission of a telescope is feasible from balloon because the tangent point is never more than 400 km from the balloon (and usually much closer) and so the vertical smearing due to the finite FOV (1.4- 1.7 km full width) was always smaller than the fundamental 2 km limitation imposed on remote measurements by the atmospheric curvature and scale height.

Like ATMOS, the MkIV interferometer takes data in both scan directions; forward and reverse. The original motivation for doing this was to improve its duty cycle. I 1o wcvcI, it is important 10 recognize that if single-sided interferograms at-c taken, then it is essential to sca n in both directions so that certain types of systematic error can cancel when the forward and reverse spectra are a veraged. On e example is that changes in solar brig htness during an interferogram alters the relative depth of' the bread and narrow spectral features. A decrease in solar intensity d uri ng a forward run would weaken the sharp spectral lines (formed primarily by the high 01'1) portion of the interferogram), whereas during a reverse run the sharp spectral lines would be strengthened. If only forward runs (single-sided) were recorded during an extended period of solar dimming (e.g. sunset), systematically low column abundances would be retrieved. 1 lowever, if forward and reverse runs were averaged with equal weight, this bias is eliminated.

Since September 1 989 nine balloon flights have been conducted; seven from Ft. Sumner, New Mexico, one from Daggett, California, and one from Lynn Lake, Manitoba. Since the MkIV usually flies with other instruments on the same gondola the total payload weight can be as large as 1500 kg. Float altitudes were in the range 36 to 41 km depending cm the total payload weight and the type of balloon. The balloon operations (launch, control, termination and recovery) were conducted by the National Scientific Balloon Facility (NSBF). Ascent to float altitude typically took 1 60 minutes after which the balloon drifted with the wind. The only control that one has over the balloon trajectory is in the ability to change altitude, either by dropping ballast or by op ening vent valves on the top Of the balloon. The flight 1S terminated by command from the ground, usually when the balloon is over flat, accessible terrain. The balloon is separated from the parachute, on which the gondola takes about 40 minutes to reach the ground

Observed from the ground, the sun is only 40% as bright as seen from balloon float altitude at sunset (coincidentally, this figure is the same for both the HgCdTe and the InSb signal chains). To prevent saturation of the signal chains during balloon flights the preamplifier gains were adjusted pre-flight to provide about 35% of a full scale signal from the ground. With these gains, the full instrument aperture would nearly saturate the digitizer at sunset. To prevent saturation at higher solar angles we could command an adjustable iris, driven by stepper motor, in areal steps of 5% at any time during the balloon flight. The advantage of in-flight aperture reduction, rather than pre-amplifier gain reduction, is that it reduces the amount of detection non-linearity (because the photon fluxes are kept smaller) and considerably simplifies its correction (because the photon fluxes remain practicably constant throughout the flight). The loss of signal-to-noise ratio resulting from aperture reduction is inconsequential because (i) the high sun spectra have very good signal-to-noise ratios anyway because of the long available integration time, and (ii) the detectors (especially InSb) are nearly digitization-limited anyway, so that provided the digitizer is filled, the signal-to-noise ratio cannot be improved further. We believe that it is far more important to minimize the systematic errors which arise from detection non-linearity than it is to marginally improve the signal-to-noise ratio of the high sun spectra. Adjusting the ii is accomplishes this: Not only are the noon photon fluxes incident upon the detector reduced, but they are also held practicably constant throughout the entire flight, maintaining the same non-linearity correction for all spectra, high sun and sunset. This consistency between high and low sun spectra is important because it minimizes biases which could otherwise distort the shapes of vmr profiles.

As the sun sets at a constant angular rate, the tangent points get further away from the balloon. This means hat the tangent height separation of successive spectra gets larger and larger unless a way is found to take spectra faster. Since the sampling speed of the MkIV Interferometer is fixed at 10 kHz, the only way we can take spectra faster is to shorten tile maximum optical path difference. So, when the solar zenith angle exceeded 93° we switched from 66 cm (104 s per spectrum) to 33 cm (54 S per spectrum) optical path difference. The consequent loss of spectral resolution is actually not that serious because the atmospheric absorption lines start to become pressure broadened anyway below 25 km altitude.

We conclude that while it is true that the broad-band (or survey) approach employed by the MkIV instrument offers less precision than narrower-band species-specific approaches, the error budgets Of most gases Of interest are actually dominated by systematic terms such as uncertainties in the viewing geometry, and in the forward model (e.g. missing spectra] lines, zero offsets, ILS distortions). Since the high resolution survey approach allows many of these dominant systematic error terms to be understood, and thereby minimized or even corrected, it is ultimately more accurate anti useful. For example, (i) The availability of CO_2 lines, having a wide range of strengths and temperature dependencies, greatly reduces systematic errors due to uncertainties in the viewing geometry or the temperature profile, (ii) the availability of narrow, isolated spectral lines having a range of strengths allows a very thorough instrument characterization (instrumental line shape, zero offsets) to be performed, (iii) the use of multiple absorption ban~is/lines of widely different strength allows high retrieval accuracy to be maintained over a considerable range of absorber concentrations and hence altitudes. Furthermore, the simultaneity and co-locality of the observations of the various gases permits more stringent model comparisons than would be possible if fewer gases were measured or if the various gas profiles were not all in the same airmass.